Production Planning at Winstone Aggregates, Including Competitors

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Abstract

The Auckland aggregate market is estimated to be 7.2 million tonnes a year. Sixteen major quarries supply this market. Because of the number of suppliers and the variety of products, planning in this complex environment is difficult.

Winstone Aggregates is the largest producer of rock products in Auckland. It owns nine quarries and supplies slightly more then half of the region's aggregate needs. This paper describes a model of the Auckland aggregate market developed as a decision making tool for Winstone Aggregates. It also describes some of the methods used to collect information for the model. A Windows interface was developed to make the model easy to use.

1 Background

Aggregates are vital for the infrastructure needs of any city. They are used for the construction of roads, motorways, office buildings, homes, drainage, and water treatment systems.

Within the Auckland region in 1997, aggregate production was forecasted to be 7.5 tonnes of aggregate per head of population [1], the actual figure is not precisely known at this time. This production is forecast to increase to 8.5 tonnes per person by 2001.

Aggregate use in Auckland is at a level that will deplete several sources of rock within four to six years [1]. These sources (the most notable is Mt Wellington Quarry owned by Winstone Aggregates), supply about 50% of Auckland's current aggregate demands. Planning strategies to retain and increase market share in this environment, is the main problem the decision making tool outlined in this paper is intended to solve.

This paper describes both the formulation of the model, and methods used to obtain the parameters it needs. The model includes quarrying operations in the Auckland area, from extraction of resource to the transportation of products to consumers within the Auckland region.

Supply parameters are determined by quarry resources, limits from resource consents, crushing and processing plant capacities, stockpile costs and transport costs. Demand parameters include roading demand by council area, as well as concrete and asphalt plant demand based on actual plant locations. The price paid for aggregate is modelled in four regions.

The allocation of the quarry output to satisfy demand was formulated as a linear program (LP). The objective of the LP was to maximise the sum over each quarry of the quarry's *Cash Contribution* (revenue minus costs).

The linear programming model was formulated with the *GAMS* [2] modelling language. Microsoft Visual basic was used to program a Windows interface to manage a Microsoft Access database. This database contains all the modelling parameters; the results are viewed automatically with Microsoft Excel.

1.1 Other Work

Within the Department of Engineering Science at Auckland University, Butt and Ryan [3] have carried work on similar production planning problems. Butt and Ryan developed a linear programming model of chicken production for Tegel Chicken with GAMS [2]. Their model gave the optimal steady state production of chicken to give the highest profit, and included Tegel's factory, storage and transportation network. The production plans indicated where to produce and where to store and sell chicken products. Parnell [6] worked on a fourth year project that took this model and extended it to solve the time staged problem to provide an optimal schedule over several weeks.

Their work was the basis for the model developed by Mitchell [5]. In this paper the model presented by Mitchell is refined, and enlarged to include competitors and pricing information.

Other work involving chicken production was described by Taube-Netto [7]. In his paper, Taube-Netto investigated the techniques and effects of operations research methods applied to Sadia Concordia in Brazil. These methods were used to improve bird production and sales.

Carino & LeNoir [4] investigated using a model developed with SAS/OR (Statistical Analysis System/Operations Research). This model was developed to provide least cost purchase strategies for wood at Wellborn Cabinet Inc., in Alabama, in the US. The model contrasted different sources (the company's own plant and outside sources) and differing order sizes.

2 Motivation for model

The most important problem Winstone Aggregates needs to investigate, involves the development of new quarries. Due to the depleted resource in Auckland, new quarries have to be opened elsewhere. Currently plans involve sites north of Albany and south of the Bombay Hills. The problem is to find least cost solutions for questions such as:

- Which quarries should be opened first?
- When should the quarries be opened?
- How should production begin in these quarries?
- How should the depleted quarries be wound down?

Winstone Aggregates would like to efficiently allocate production among its nine Auckland quarries. Given market forecasts of the type outlined in the 1997 University of Auckland report [1] the would allow them to set up production plans, allocating production amongst their quarries, over a year or several years.

3 Physical Description

This section describes the underlying physical processes that give rise to the model formulation.

3.1 Quarry Locations

Winstone Aggregates owns nine quarries spread over the greater Auckland region. The quarries are located on the Auckland isthmus from Flat Top quarry north of Albany, to Pukekawa quarry south of the Bombay Hills. Of these quarries, Mt. Wellington is by far the largest, producing 60% of Winstone Aggregates Auckland production.

3.2 Resources

The Winstone Aggregates quarries in Auckland contain a range of resources: Sand, Scoria, Basalt and Greywacke. Each resource produces different products.

A process called weathering determines the quality of basalt and greywacke rock. Weathered basalt and greywacke is of a lower quality than unweathered rock. A basalt or greywacke quarry face will contain rock of different qualities. The weathered rock will be on top part of the face; the high quality rock will be near the bottom. The proportion of low quality weathered rock to high quality unweathered rock can be considered constant on the face. The proportions will depend on the geology of the area.

It is not possible to only extract only the high quality rock from the quarry face, as the whole of a face must be quarried. For this reason, the proportion of high and low quality rock quarried at any particular quarry is considered constant over a year. There is some flexibility however, in shorter periods it is possible to quarry more of a particular resource.

3.3 Resource Consents

Most of the quarrying operations in Auckland are governed by the Resource Management Act 1991. The act states that one of its purposes is to manage resources while:

> **Section 5 c)** Avoiding, remedying, or mitigating any adverse effects of activities on the environment.

Resource consents issued by the council under this act generally restrict the amount of rock that can be extracted from a quarry, within a year. Not all quarries are limited by their resource consents. Hunua Quarry has open-ended resource consent and an unlimited amount of material may be quarried. Mt Wellington is limited by a commitment to quarry only 1.1 million cubic metres, a year, due to the depleting resource available.

3.4 Processing

Once the rock or sand is quarried, it undergoes processing. In basalt quarries, a large crushing machine crushes the rock. The crushed rock is then processed in secondary plants. Throughput and the number of operating hours determine the capacity of a plant. The secondary plants produce the final products, by a combination of screening the rock to size and re-crushing.

The *production mode* governs the type and proportion of products made by a plant. The production mode depends on how the rock is crushed, and screened within the plant. The associated costs of running the plant also depend on the production mode. These costs are dependent on the number of people that are required to operate the plant, the wear and tear on the plant equipment (mostly screens) and utility costs.

3.5 Stockpiling and Transportation of products

Once made, products are kept in stockpiles at the quarry until they are sold. While in stockpiles the products do not deteriorate nor lose value. There is no explicit cost of keeping a stockpile, as it does not have to be warehoused. A capital cost is charged in the model. This cost is 10% per year of the total cost of production, of the stockpile.

Transportation of aggregate incurs a cost. Winstone Aggregates transports between one-half to a third of its products. The individual customers or sometimes a third party transport the rest. The model charges a transportation cost on all aggregate. This is to ensure that Quarry production is close to the market. Transportation costs are considered solely dependent on distance. The model charges a cost of 7.4 cents per kilometre per tonne. This cost is based on the rate charge by Winstone Aggregates.

4 Formulation of model

The linear programming model follows Winstone Aggregates business from extraction to sale. The model will be described in terms of its GAMS implementation.

4.1 Sets

The index sets that the model uses are as described below. The lower case letters in the brackets indicate the indices.

- **Quarries (q).** Nineteen quarries are currently represented in the model. The quarries in the model are nine Winstone quarries, six competitor quarries and two *pseudo quarries*. These two *pseudo quarries* are added to make up for the number of smaller quarries that supply the Auckland market from the North and the South. The model does not distinguish between competitor and Winstone quarries.
- **Plants (pl).** This refers to the individual processing plants in the quarries that operate simultaneously to process aggregate. Currently this set is only important in Mt. Wellington (which has three plants) all other quarries are modelled as a single plant.
- **Resources (r).** There are five different kinds of resource they are, High, Medium and Low Grade Basalt, Scoria and Sand. Greywacke is included in the Basalt classification as both resources produce almost the same products; also, no quarry contains both Basalt and Greywacke
- **Production modes (ps).** The production mode is the manner in which the plant is operating. In the current model, there is not more than one production mode per plant. This is a consequence of simplification of the data. This set is useful for modelling plants in more detail; it can also be used to examine forecast supply scenarios.
- **Products (p).** Winstone Aggregates produces over 80 different products in the Auckland region. To simplify the model the products were aggregated into eight groups: Scalpings, Low and High Grade Basecourse, Coarse and Fine Aggregates, Sealing Chips, Scoria and Sand These product groupings reflect how the products are made, and

sold. They serve to remove the complexities caused by changing screen sizes and other minor changes in the processing plants.

- **Markets (m).** Each market represents a customer or region that purchases quarry products. A detailed description of how demand is modelled follows in section 5 below.
- **Time Staging (t).** The model is time staged by 3-month quarters. Quarters were used because they reflect the seasonal nature of the demand. The production in each quarter is linked by the stockpiles of product. Currently the model solves each year as a separate linear program linked by the stockpiles. This measure was taken to reduce the size and solution time of the model.

4.2 Objective

The objective of this model is to maximise the total profit earned by all the quarries in the Auckland region. The objective function is Equation 1:

$$\max\{P = R - C\} \quad \textbf{(1)}$$

$$C = \sum_{t} (CT_t + CP_t + CS_t) \quad \textbf{(2)}$$

where

- R is the total revenue from the quarries
- C is the total cost of production
- $\boldsymbol{CT_t}$ is the transportation cost of period t
- $\boldsymbol{CP_t}$ is the production cost of period t
- $\boldsymbol{CS_t}$ is the cost of stockpiles in period t

4.3 Constraints and variables

The formulation of the linear program is set out below. The constraints are listed in an order that follows the physical operations in the quarry.

$$\sum_{r,t} (R_{q,r,t}) \leq M_q \quad \textbf{(3)}$$

$$\sum_{t,r'} (R_{q,r',t}) \cdot RP_{q,r} = \sum_{t} R_{q,r,t} \quad \textbf{(4)}$$

$$L_{pl,q,t} \geq \sum_{r,ps} PST_{q,pl,r,ps,t} \quad \textbf{(5)}$$

$$CP_t = \sum_{q,pl,r,ps} (PST_{q,pl,r,ps,t} \cdot PC_{pl,r,ps,q}) \quad \textbf{(6)}$$

$$R_{q,r,t} = \sum_{ps,,pl} (PST_{q,pl,r,ps,t} \cdot MPS_{q,pl,r,ps}) \quad \textbf{(7)}$$

$$\sum_{m} QPM_{q,p,m,t} + S_{q,p,t} = \sum_{pl,r,ps} (PST_{q,pl,r,p,s,t} \cdot MPS_{q,pl,r,ps} \cdot PS_{p,q,pl,r,ps}) + S_{q,p,t-1} \quad \textbf{(8)}$$

$$CS_t = \sum_{q,p} (S_{q,p,t} \cdot SC_{p,q}) \quad \textbf{(9)}$$

$$D_{p,m,t} = \sum_{q} QPM_{q,p,m,t} + DS_{m,t} \quad \textbf{(10)}$$

$$CT_t = \sum_{q,p,m} (QPM_{q,p,m,t} \cdot TC_{m,q}) \quad \textbf{(11)}$$

$$R = \sum_{q,} (DP_{p,m,t} \cdot QPM_{q,p,m,t}) \quad \textbf{(12)}$$

where

- ***Rq,r,t*** is the variable that shows amount of each resource removed from the quarry in a period.
- $\boldsymbol{M_q}$ The maximum amount of rock that can be mined in a year. This parameter is largely dependent on the individual resource consent for the quarry.
- $\boldsymbol{r'}$ is a copy of the set of resources.
- $\boldsymbol{RP_{q,r}}$ The proportions of resource in each quarry. The information in this parameter represents the particular geology of the quarry.
- $\boldsymbol{L_{pl,q,t}}$ The number of days that each plant can produce per period.
- $\boldsymbol{PST_{q,pl,r,ps,t}}$ is the amount of time spent on each production mode in each period.
- $\boldsymbol{PC_{pl,q}}$ The cost of operating a plant for a day. The method that was used to find it was the cost of production divided by the number of days the quarry operated.
- $\boldsymbol{MPS_{q,pl,r,ps}}$ The capacity of a particular production mode in a single day. The figures were based on an average ten-hour weekday.
- $\boldsymbol{QPM_{q,p,m,t}}$ is the amount of each product sold and transported to each market from each quarry.
- $\boldsymbol{S_{q,p,t}}$ is the amount of each product left in stockpiles in the quarry, at time t.
- $\boldsymbol{PS_{p,q,pl,r,ps}}$ the proportion of products made in a day in different operating modes in each plant.
- $\boldsymbol{SC_{p,q}}$ The cost of stockpiling product in a quarry. The stockpiling cost was worked out as a charge for the money that is invested in the stockpile. The charge is 10% per annum of the production cost of the stockpile (the tonnage times the cost per tonne).
- $\boldsymbol{D_{p,m,t}}$ The demand for each product in each market during each quarter. The method used to arrive at this figure is show in section 5 below.
- $\boldsymbol{DS_{m,t}}$ is the amount of shortfall to each customer
- $\boldsymbol{TC_{m,q}}$ The cost of transporting product from quarry to market. The cost of transportation depends on the distance that the trucks have to carry cargo. This distance was found from a map of the Auckland region.
- $\boldsymbol{DP_{p,m,t}}$ the price paid for each product by the market this method used to obtain this figure is shown in section 5 below.

Equation 4 is a constraint needed to keep the resource proportions quarried constant over a year, but of certain resources can be concentrated in the quarter that they are needed.

Equation 7 states the amount of each particular resource that flows through the processing plants has to be equal to the amount that is actually quarried, as the raw resource is not stockpiled.

To clarify equation 8,

$$PST_{q,pl,r,p,s,t} \cdot MPS_{q,pl,r,ps} \cdot PS_{p,q,pl,r,ps}$$

is the total amount of product made in a quarry. This is the amount of time spent on each production mode, multiplied by the total number of tonnes processed, multiplied by the proportion of product made in that mode.

Equation 8 controls the stockpiles and distribution. Once products are made they are stockpiled. The stockpiled products are either sold, in the quarter that they are made, or kept in the stockpile until the next quarter. The stockpiles consist of products made in the quarter or products that were left on the stockpile from the last quarter.

Equation 10 states that demand by customers that is not met by the quarries is a shortfall

5 Parameter Information

The Second part of this paper describes methods used to estimate the parameter information in the model.

5.1 Supply Modelling

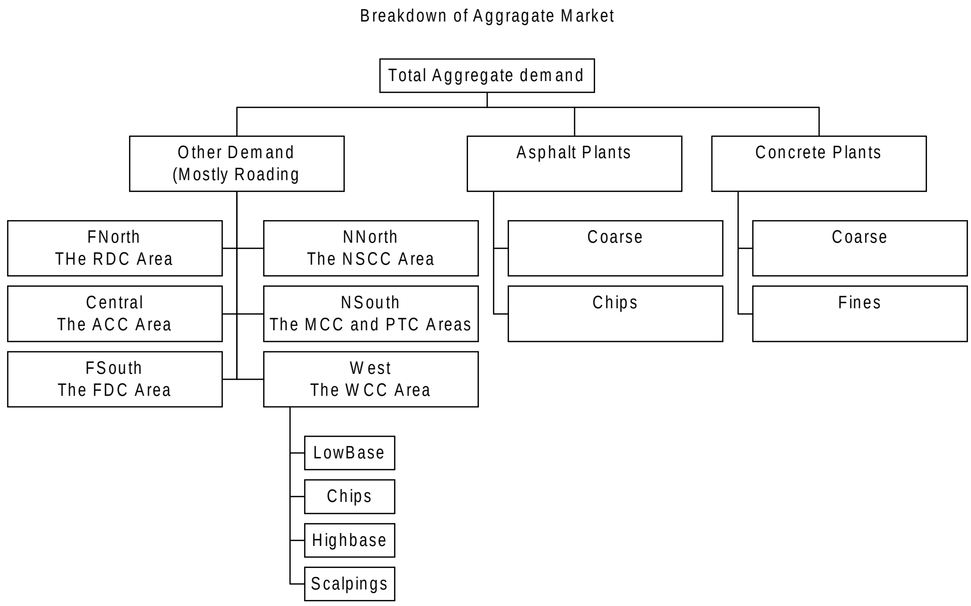
The parameters modelling the capacity and costs of the Winstone quarries were easily obtained from Winstone Aggregate's accounting information. The competitor quarry information was harder to obtain. Estimates of the capacity information and the product proportions were obtained from Winstone staff. The costs were assumed to be 85-95% of the equivalent Winstone quarry.

5.2 Demand Modelling

The improvement in the model outlined here over that presented by Mitchell [5] is competitors are explicitly modelled. Since competitors do not release sales figures the method below was used to find the total market.

The range of products was reduced from those covered in Mitchell. Sand and Scoria products were not included. This was because the markets in these two products is predicted to be static over the next 5 years (the planning horizon in this paper). The quarries producing Scoria and Sand are also less numerous then hard rock quarries so the respective markets are less complex.

The market model is broken into three groups. Concrete and Asphalt plants, and Roading demand. Concrete and Asphalt plants are located by suburb; each individual plant is entered along with its demand requirements. Due to the wide spread nature of roading consumers, six geographic zones represent the market. The different markets are divided along council boundaries. The market model is shown diagrammatically in figure 1.



1: A diagram of the demand model

The demand for the concrete and asphalt plants were based on the supply figures from Winstone Aggregates, market share figures were used to calculate the total demand.

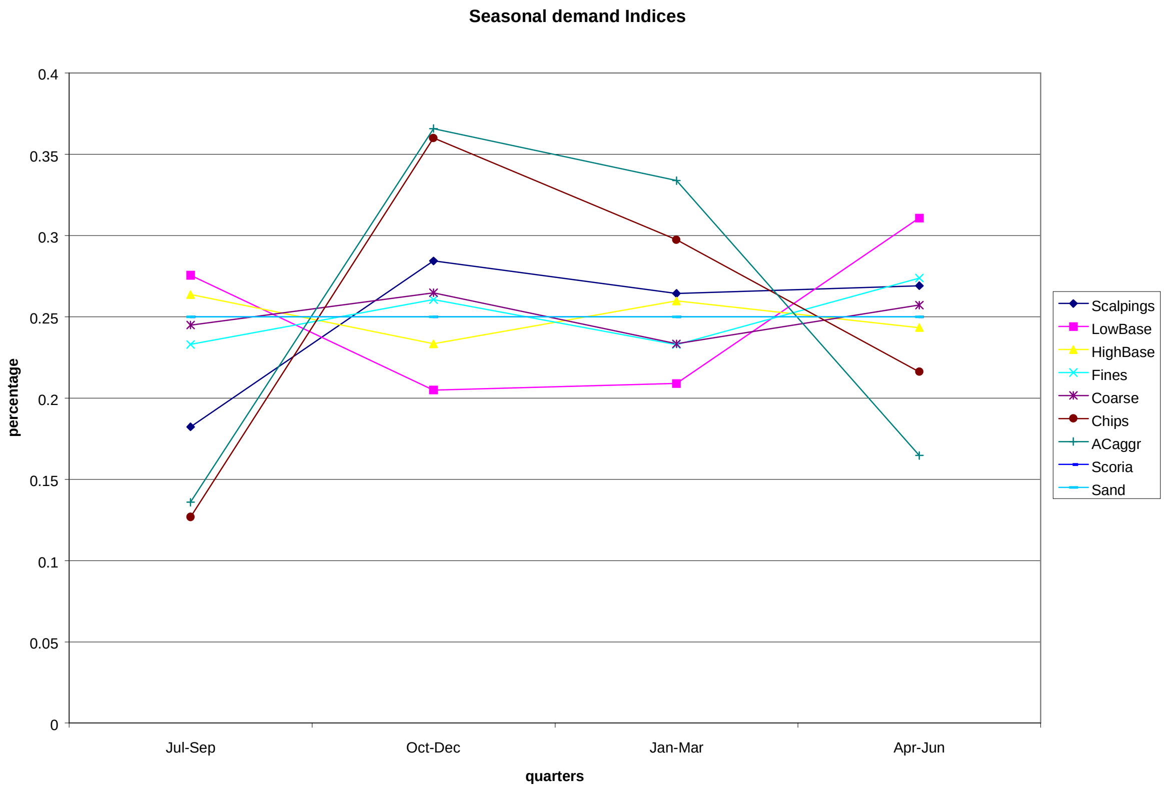
The demand figure for the roading market segment was much harder to estimate, as accurate market shares were not available. The Winstone figures were again used a starting point; the market share was estimated for each product and region. This figure was then compared to the quarry output estimates in order to check and verify.

These figures were then entered into a Microsoft Excel spreadsheet. A sheet was created that divided the top line figure for demand into the individual demands. Then the demand for future years was calculated using the same proportions, but with forecast top line figures.

5.2.1. Products and Seasonal variations

The method outlined above generates yearly demand figures. As the model works on a time period of quarters the demand should be divided into quarters.

The demand for some aggregate products is very seasonal. This seasonal nature as shown in figure 2 below. Simply dividing yearly demand into 4 for each quarter is inaccurate. Seasonal data was obtained from figures of monthly sales from Mt. Wellington only. Mt. Wellington was used because it supplies 60% of the Auckland sales; it was also the only quarry for which data was available. The sales of Sand and Scoria products were assumed constant, as there was no data available.



2: Seasonal Indices of Sales, by Product Grouping

The seasonal variations are modelled by including a seasonal index for every product. These indices are proportions that divide the total yearly figure into the quarters used in the model.

5.2.2. Price Modelling

As this model maximises the total revenue the price structure of the market needs to be modelled. The market is divided up into the council regions mentioned above. Every product in each region is then given an average selling price.

These selling prices were determined from the ex-quarry discounted prices, i.e. prices without a transportation cost. A figure for the average transportation cost was then added. This transportation cost is found by including the average distance, from the nearest quarry that supplies the product into the region.

6 Implementation and Interface

This model is formulated in the GAMS modelling language [2]. The BDMLP solver was originally developed at the World Bank by Brooke, Drud, and Meeraus and is now maintained by GAMS Development[1]. This is the free solver that was included with GAMS when the PC version was purchased. GAMS was installed on an Intel Pentium II 233MHz processor with 64mb of RAM. The time taken to solve the model is around 15 minutes.

Due to the large number of parameters, the parameter information for the GAMS file is stored separately from the model formulation. The parameters are entered into a Microsoft Access database. The Access database is accessed through a Microsoft Visual

[1] http://www.gams.com

Basic application, which was written for this purpose. This application converts the parameters into the flat ASCII files that are needed to input as GAMS include files.

Once GAMS has generated a solution the GAMS output is read into a Microsoft Excel workbook by the application which then generates *pivot tables*[2] from the data.

Acknowledgments

I would like to thank Dr. Steven Butt and Professor David Ryan my project supervisors for assisting me in my original project [5].

I would also like to thank my colleagues at Winstone Aggregates for their input into this paper and the time that they spent, gathering information and discussing the problem with me. I would especially like to thank Auret Vorster, David Howie, Paul Liversay, Chris Scullen, Bernie Chote, Kevin Higgins and Richard Compton.

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[2] A PivotTable is an interactive table that quickly summarises, or cross-tabulates, large amounts of data. (Microsoft Excel Help)